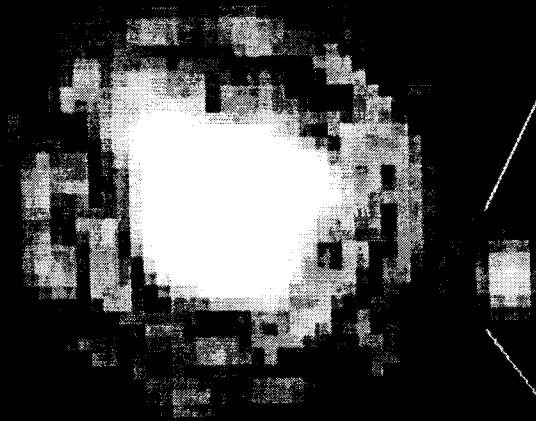


Building a Virtual Planet

V. S. Meadows, Jet Propulsion Laboratory, California Institute of Technology

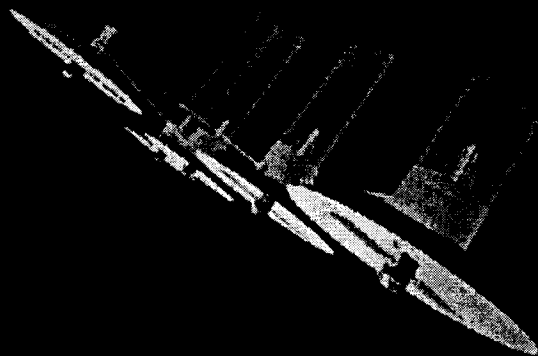
The Virtual Planetary Laboratory (VPL) is a recently funded 5-yr project, which seeks to improve our understanding of the range of plausible environments and the likely signatures for life on extrasolar terrestrial planets. To achieve these goals we are developing a suite of innovative modeling tools to simulate the environments and spectra of extrasolar planets. The core of the VPL is a coupled radiative transfer/climate/chemistry model, which is augmented by interchangeable modules which characterize geological, exogenic, atmospheric escape, and life processes. The VPL is validated using data derived from terrestrial planets within our own solar system. The VPL will be used to explore the plausible range of atmospheric compositions and globally averaged spectra for extrasolar planets and for early Earth, and will improve our understanding of the effect of life on a planet's atmospheric spectrum and composition. The models will also be used to create a comprehensive spectral catalog to provide recommendations on the optimum wavelength range, spectral resolution, and instrument sensitivity required to characterize extrasolar terrestrial planets. Although developed by our team, the VPL is envisioned to be a comprehensive and flexible tool, which can be collaboratively used by the broader planetary science and astrobiology communities. This presentation will describe the project concept, the tasks involved, and will outline current progress to date. This work is funded by the NASA Astrobiology Institute.

Building a Virtual Planet



Dr. Victoria Meadows

Jet Propulsion Laboratory/California Institute of Technology



Looking for Life In All the Right Places

NATURE · VOL 365 · 21 OCTOBER 1993

A search for life on Earth from the Galileo spacecraft

**Carl Sagan^{*}, W. Reid Thompson^{*}, Robert Carlson[†], Donald Gurnett[‡]
& Charles Hord[§]**

^{*} Laboratory for Planetary Studies, Cornell University, Ithaca, New York 14853, USA

[†] Atmospheric and Cometary Sciences Section, Jet Propulsion Laboratory, Pasadena, California 91109, USA

[‡] Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242-1479, USA

[§] Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80309, USA

In its December 1990 fly-by of Earth, the Galileo spacecraft found evidence of abundant gaseous oxygen, a widely distributed surface pigment with a sharp absorption edge in the red part of the visible spectrum, and atmospheric methane in extreme thermodynamic disequilibrium; together, these are strongly suggestive of life on Earth. Moreover, the presence of narrow-band, pulsed, amplitude-modulated radio transmission seems uniquely attributable to intelligence. These observations constitute a control experiment for the search for extraterrestrial life by modern interplanetary spacecraft.

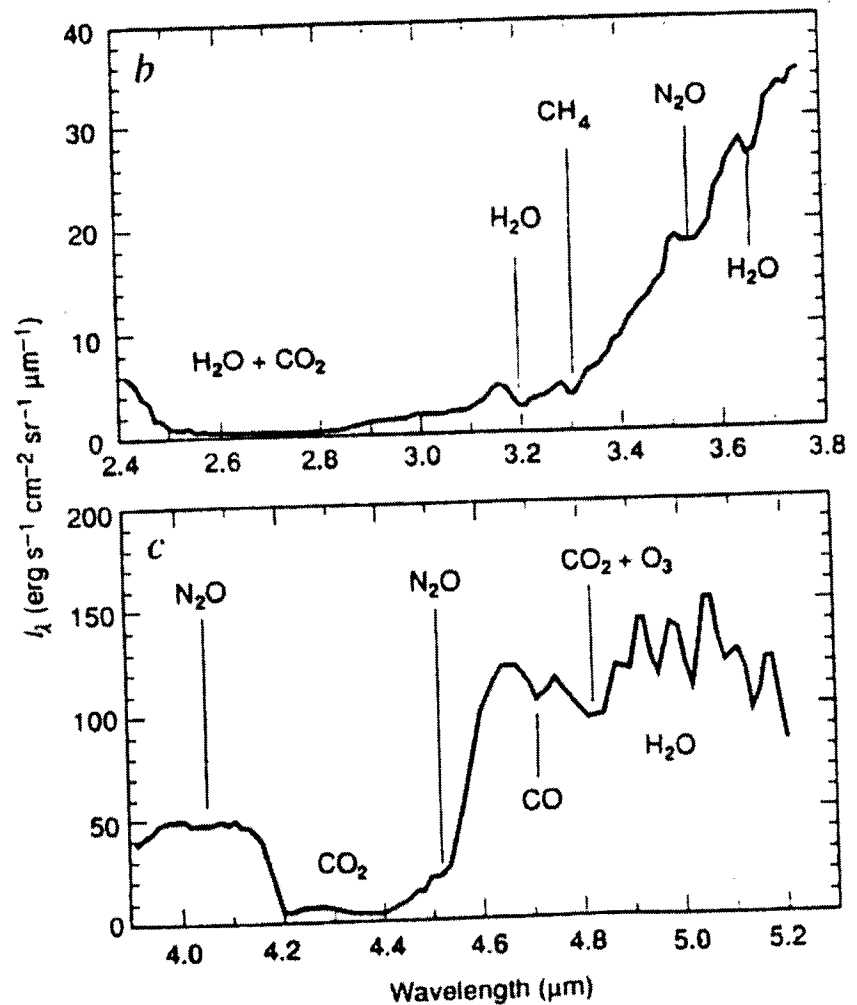
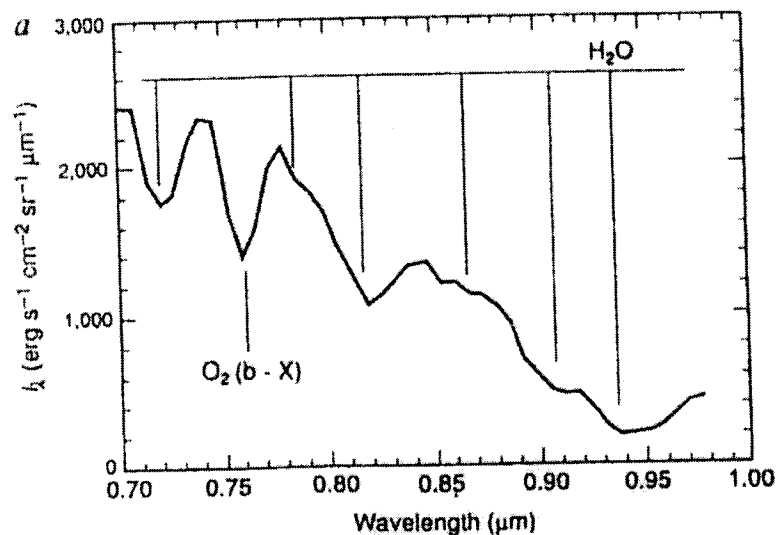
Characterizing Extrasolar Planets Observations

- **Environmental Characteristics**
 - parent star, placement in solar system, moons, other planets
- **Photometric properties and variability**
- **Remote-sensing spectroscopic analysis**
 - the presence of an atmosphere and its bulk chemical composition
 - the nature of the emitting/reflecting layer and its wavelength dependent optical properties (albedo, thermal emissivity, temperature)
 - atmospheric pressure at the “surface”, and total atmospheric mass above that surface
 - atmospheric structure (variation of T and P with altitude)
 - trace gas mixing ratios and their spatial resolution
 - temporal variations, phase and seasonal variations
- **Astronomical Biosignatures**
 - photometric, spectral or temporal features indicative of life.

Galileo's View of Earth

Remote Sensing Signatures for Life

- Spectral absorption features for
Chlorophyll
Oxygen
Methane
- Radio transmission



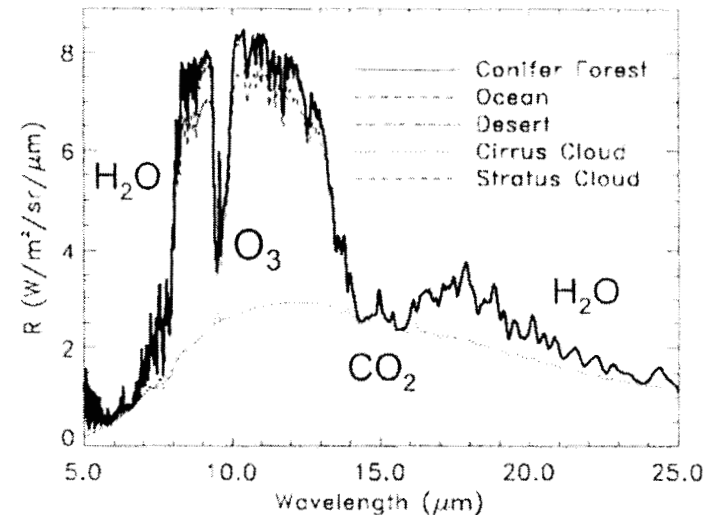
A SEARCH FOR LIFE ON EARTH FROM THE GALILEO SPACECRAFT. Carl Sagan et al. in *Nature*, Vol. 365, No. 6448, pages 715-721; October 21, 1993.

WAVELENGTH CONSIDERATIONS

(V)

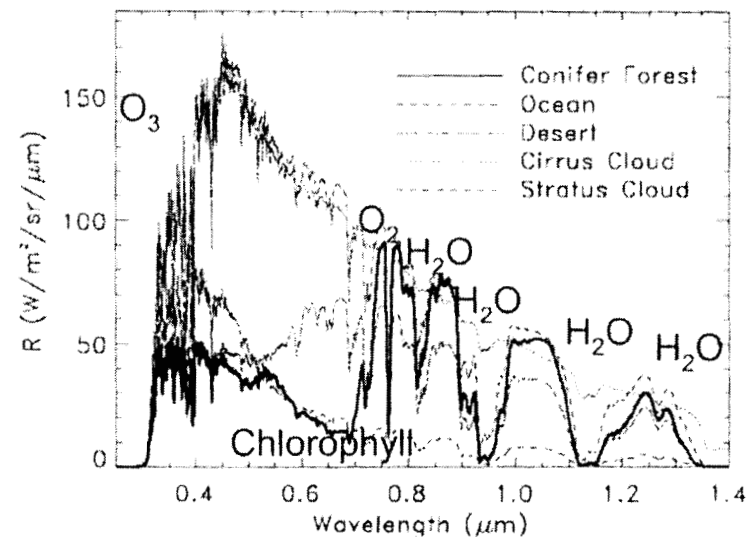
•The Mid-IR

- easiest for nulling-interferometry
- sensitive to molecular absorption
- gets us a straightforward determination of the size of the planet
- sensitive primarily to the stratosphere, compromised by high clouds

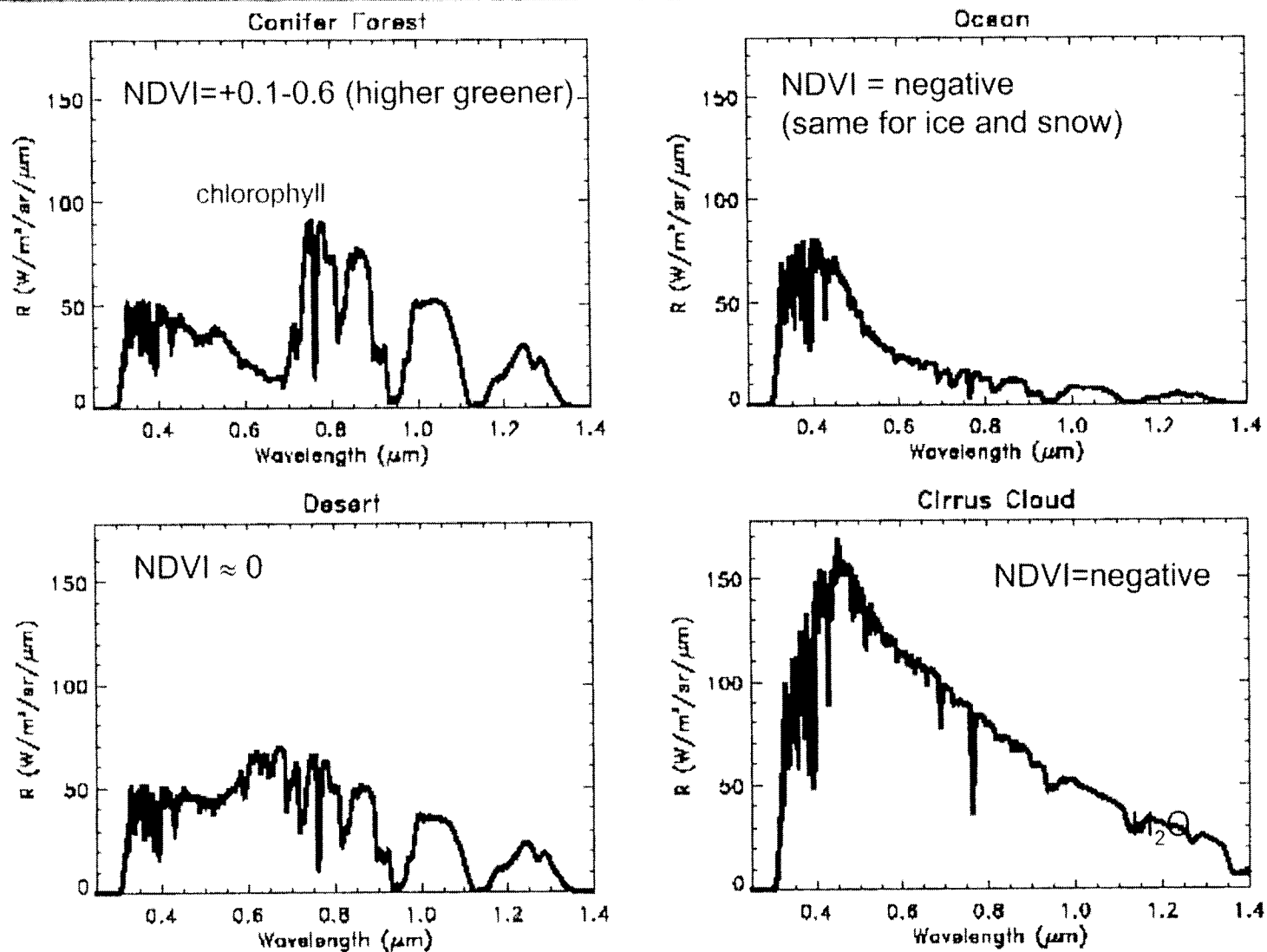


•The visible (and NIR)

- achievable with coronagraphs
- direct detection of O_2 and many other molecules
- more robust to clouds, NIR can also penetrate “clouds”
- sensitive to both atmospheric *and* surface signatures



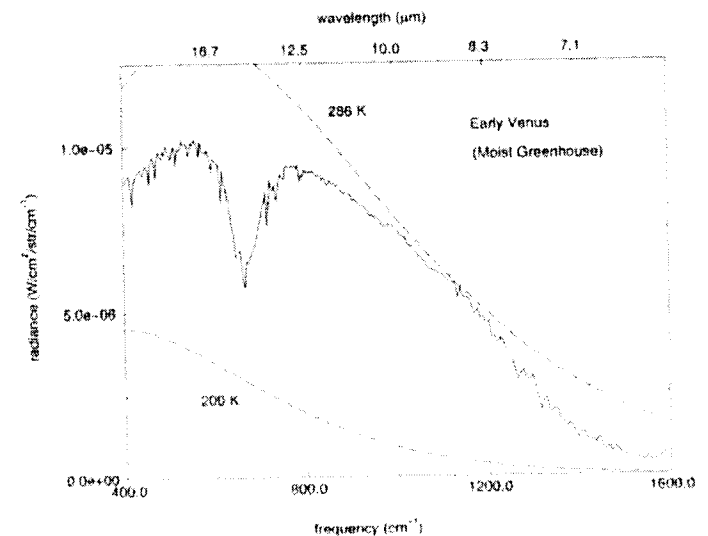
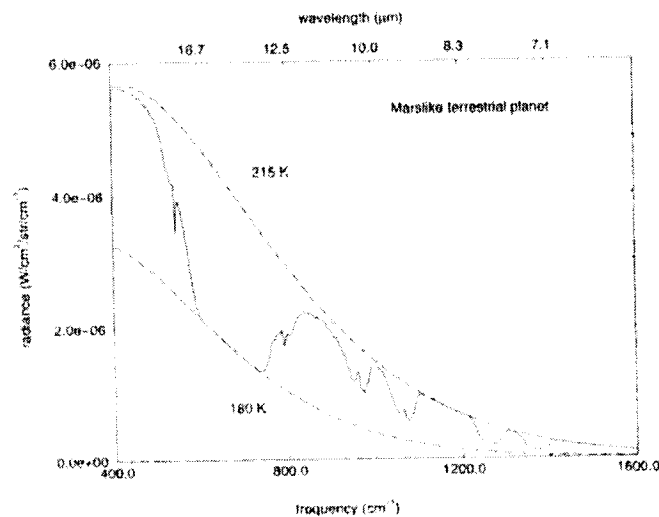
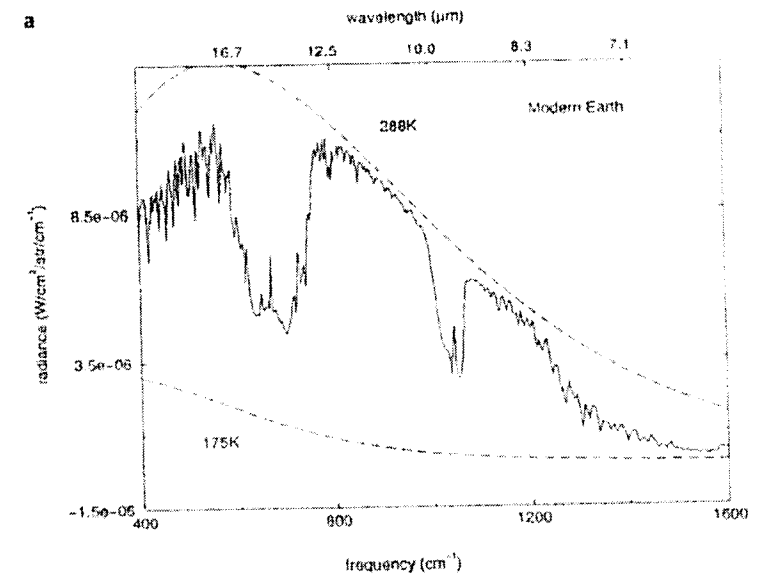
Surface Sensitivity



NDVI $(ch2 - ch1)/(ch2 + ch1)$, where $ch1=0.58-0.68\mu\text{m}$ and $ch2=0.725-1.0\mu\text{m}$

Astronomical Biosignatures

- Previous work concentrates on Earth-like planets, or planets around a G2V star.
- Some work done on “false positives”
- Schindler and Kasting, 2000
- TPF SWG JPL Pub. 01-008

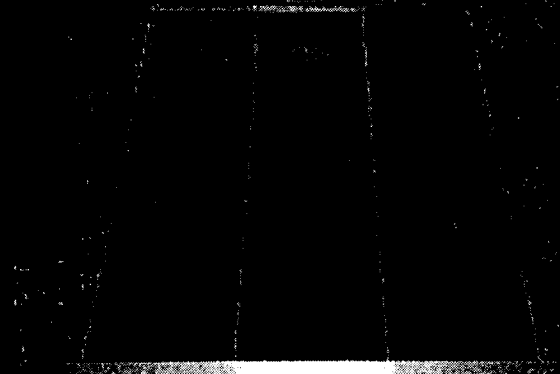
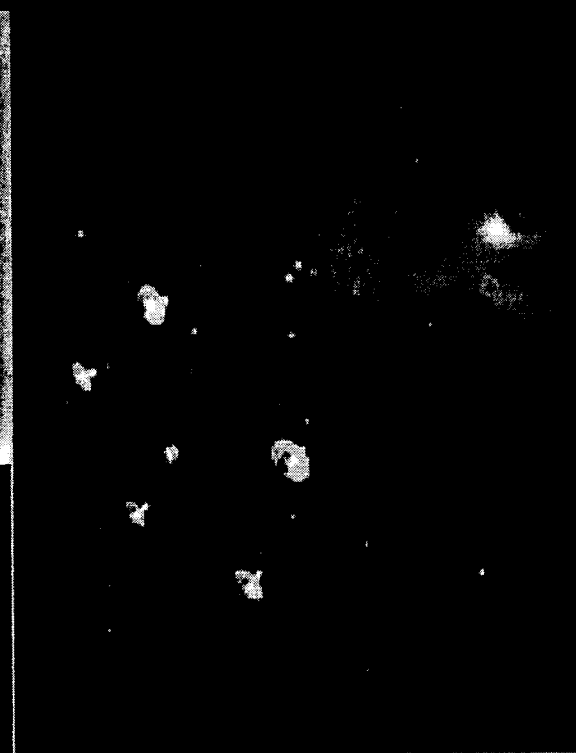
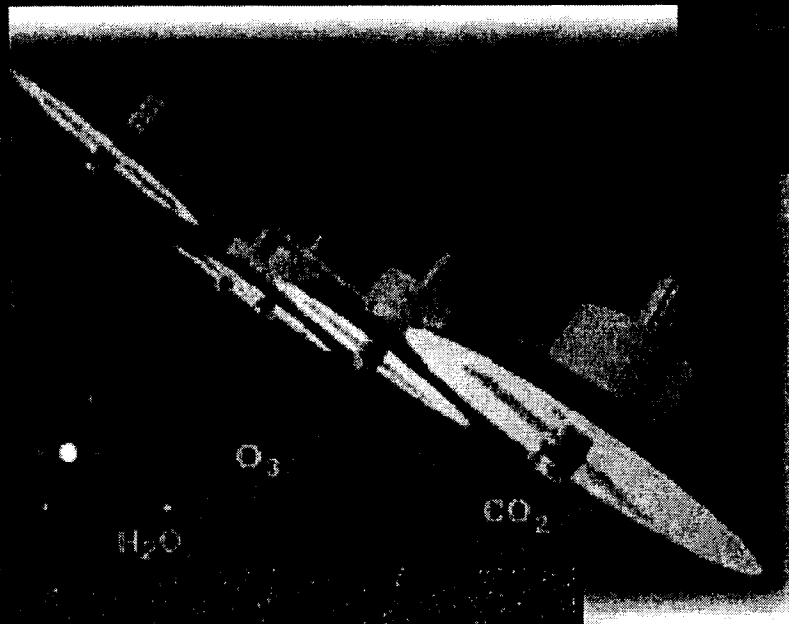


Schindler and Kasting, 2000

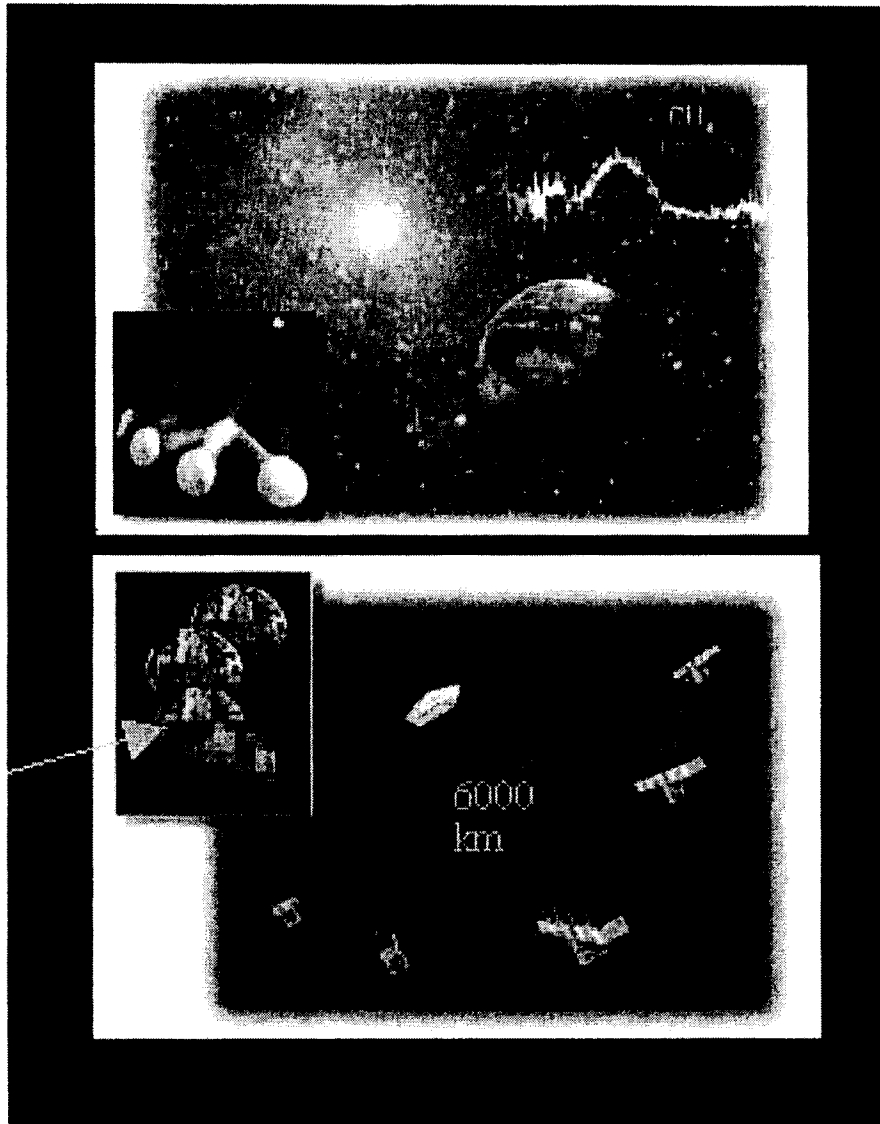
Terrestrial Planet Finder

James Webb Space Telescope

Director's Report of progress
March 2014-2015

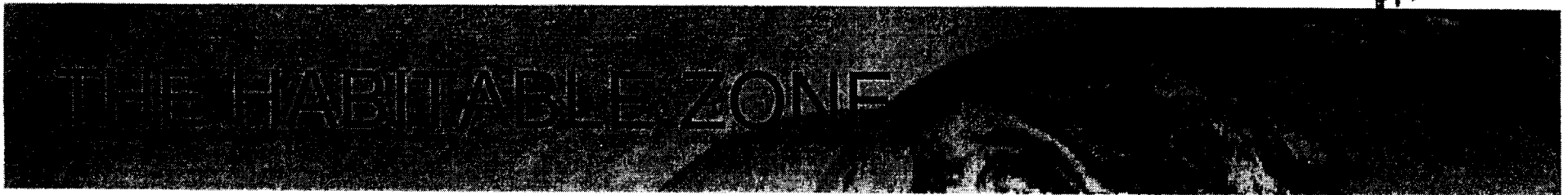


Life Finder and Planet Imager



- Life Finder (NASA)
 - chemical signatures of life
- Planet Imager (NASA)
 - spatial resolution on the disk of a planet a few light years away

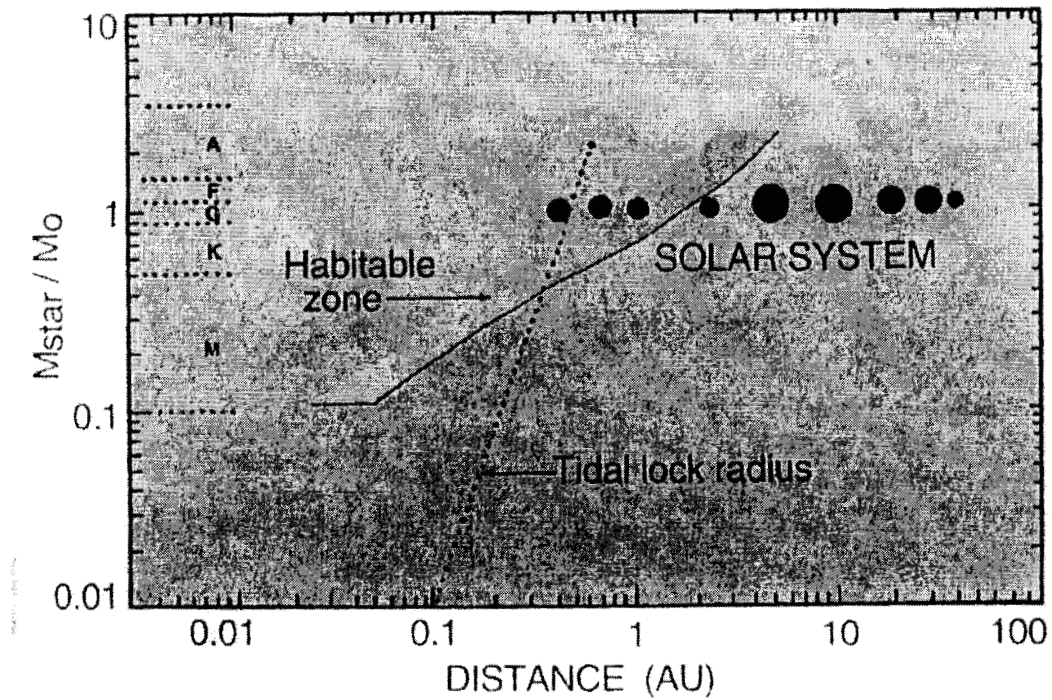
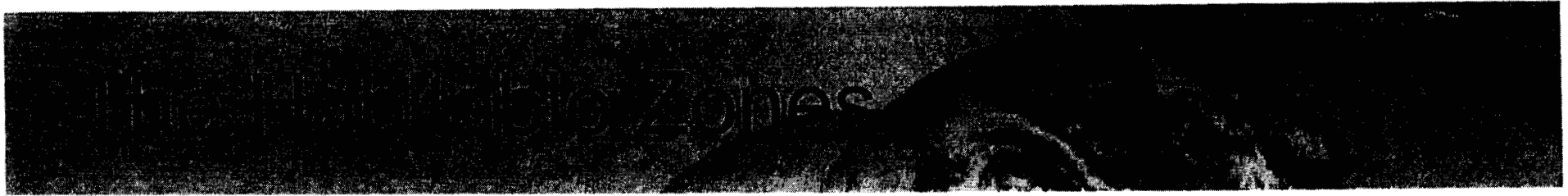
W



- The habitable zone is that region around a star in which a planet can sustain *liquid water* on its surface
- The Continuously Habitable Zone (CHZ) is the region that remains habitable over a period of time.
- Inner edge for a G2V star is conservatively set at 0.95AU
 - Earth's water lost, but assumes no cloud feedback on climate
 - cloud cooling as solar flux increases could extend this limit
- Outer edge, possibly at 2.4AU, depends on a variety of factors that are not easy to predict
 - effect of clouds on climate, optical depth, cloud height and fractional cloud cover
 - atmospheric density, greenhouse warming
- The limits of the habitable zone change with stellar type, planetary mass and atmospheric composition.

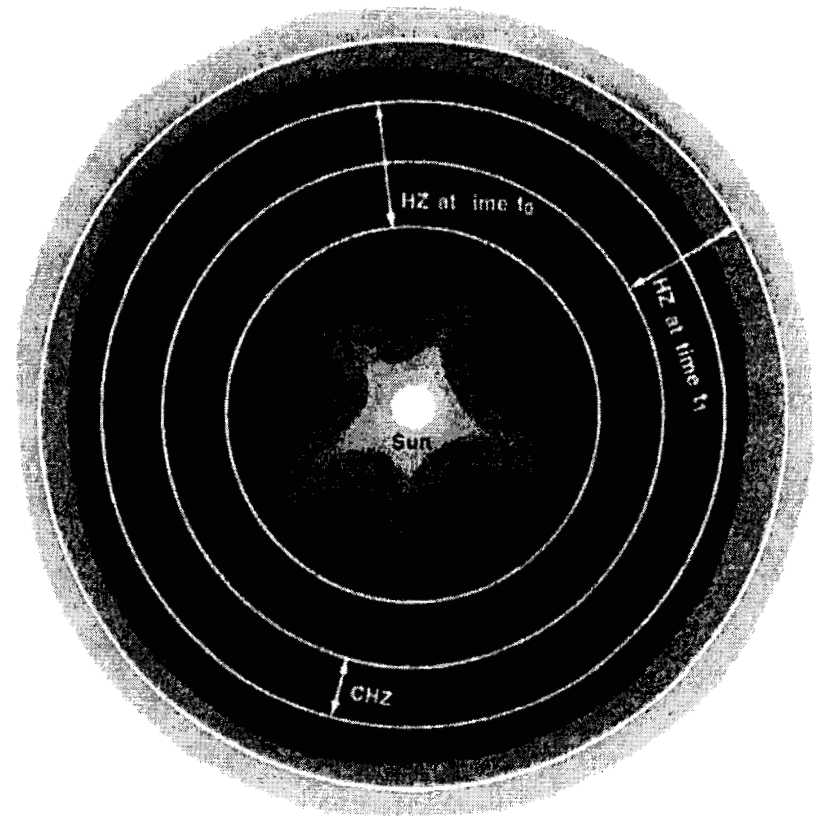
• MOST HZ MODELING HAS BEEN DONE FOR VERY EARTH LIKE PLANETS

- 1-5 R_E , m_E
- G2 STARS
- 0.95 - 2.4 AU



After Kasting, Whitmire and Reynolds, 1993.

The “Instantaneous” Habitable Zone

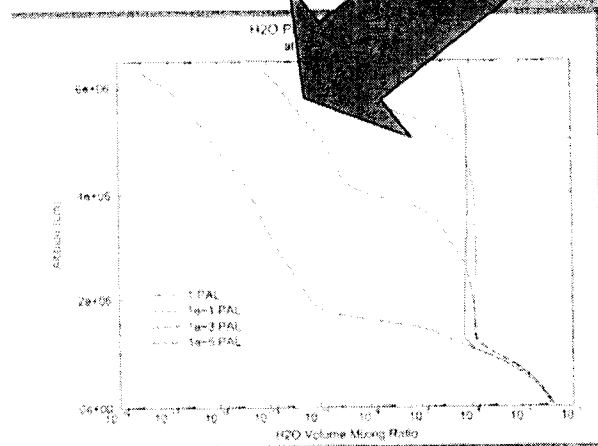


The Continuously Habitable Zone

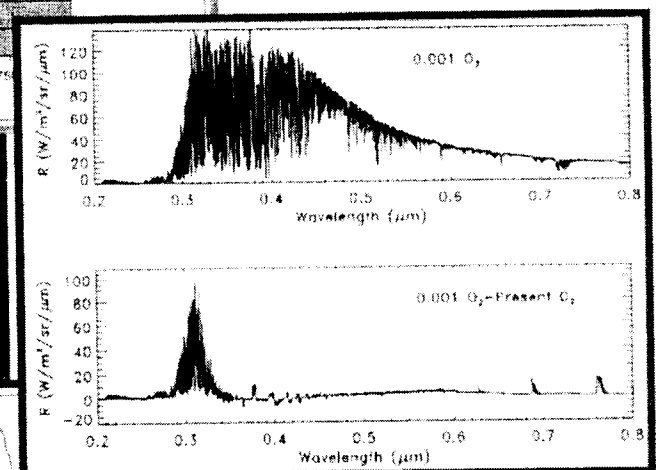
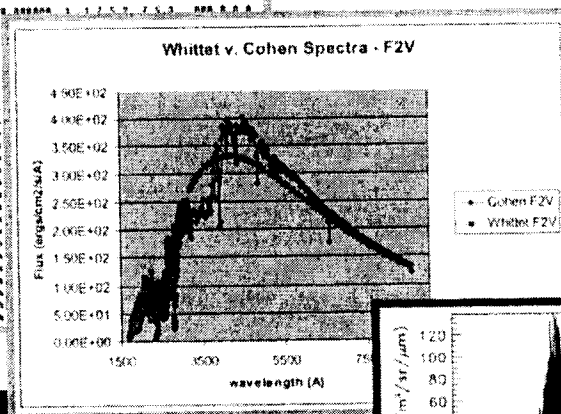
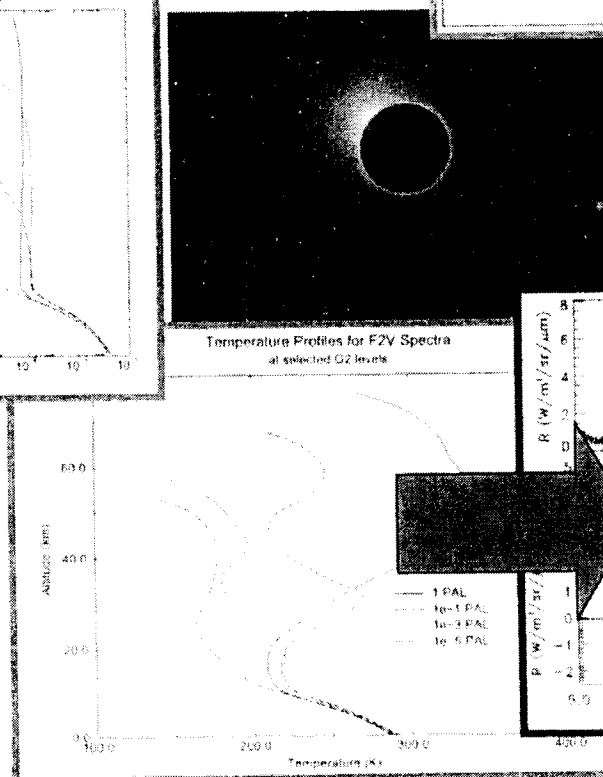
Images courtesy of J.F.Kasting.

(A)

Figure 1 is a scatter plot with a fitted curve. The x-axis is labeled 'Flux (erg/cm^2/s)' and ranges from 0 to 1.0. The y-axis is labeled 'Flux (erg/cm^2/s)' and ranges from 0 to 5.0. The data points are represented by open circles, and a solid line represents the fitted curve. The curve starts at approximately (0.1, 0.5) and increases monotonically, passing through points like (0.3, 1.5), (0.5, 2.5), (0.7, 3.5), and (0.9, 4.5). The data points are scattered around the curve, with some showing more deviation than others.



2. Climate-Chemical Model. T, Constituent distribution.

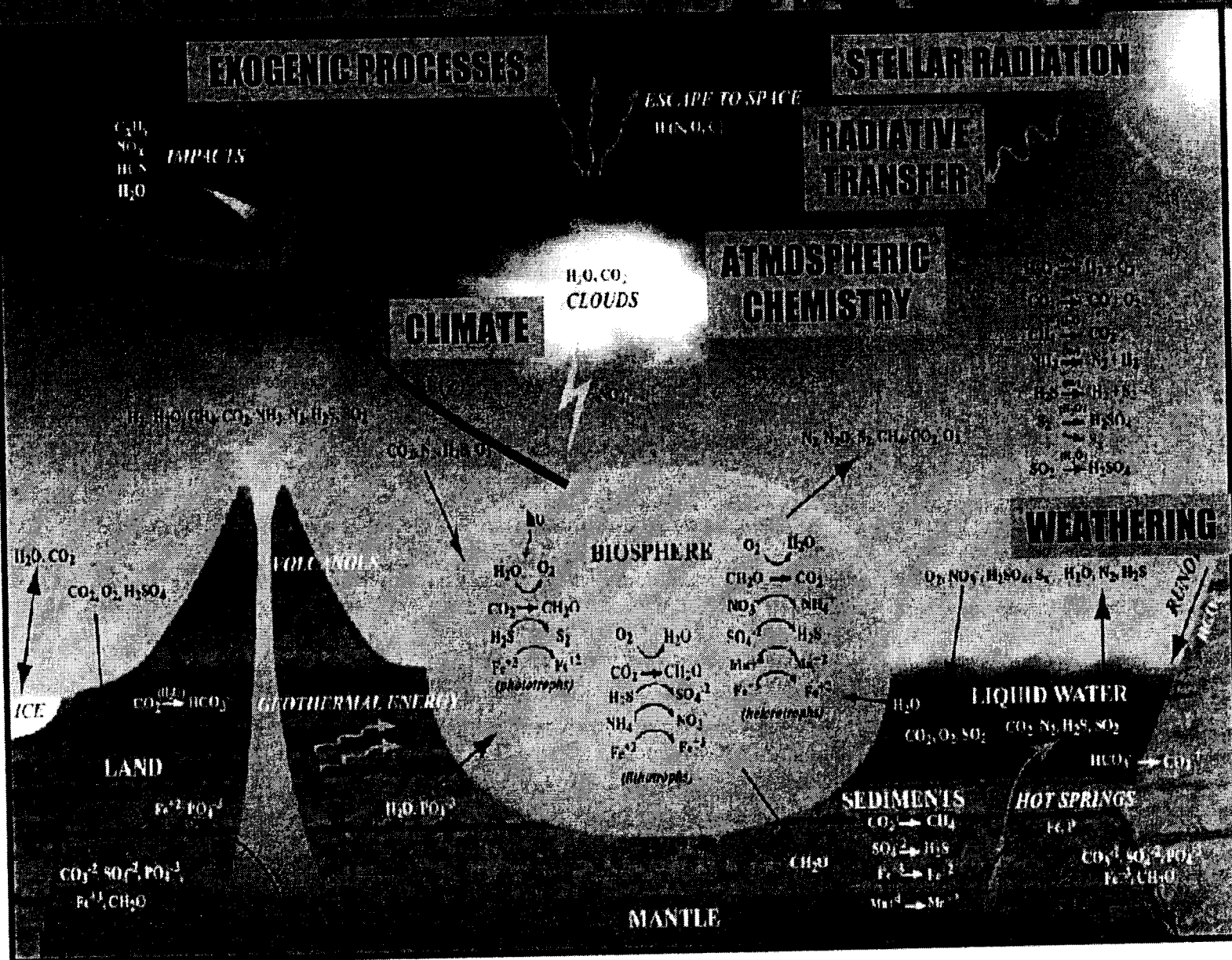


3. Radiative Transfer Model: Planetary Spectra

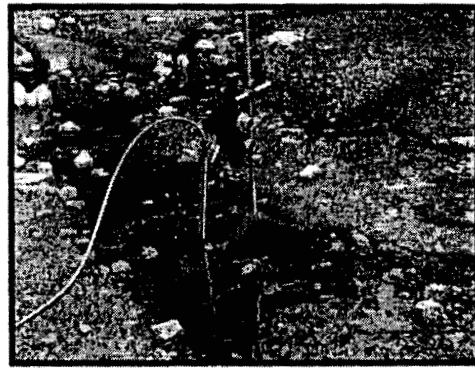
Current Challenges

- Chemical compositions must be self-consistent
- Calculations should be performed in a self-consistent manner
 - atmospheric structure and chemistry need to be coupled
- Results need to be over a large spectral range (previously solar and near infrared wavelengths tended to be neglected)
- Multiple scattering by clouds and aerosols should be treated realistically
- Detectability in a disk average needs to be explored
- The effects of attenuation by zodiacal dust and limitations in instrument performance must be considered.

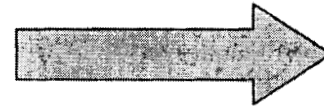
SIMULATING PLANETS AND THEIR ATMOSPHERA



Earth: Then and Now



Nymph Creek **acid hot springs** in Yellowstone contains thick **biofilms** dominated by photosynthetic algae such as *Cyanidiu*. (Photo by A. Neal, Montana State Univ.)

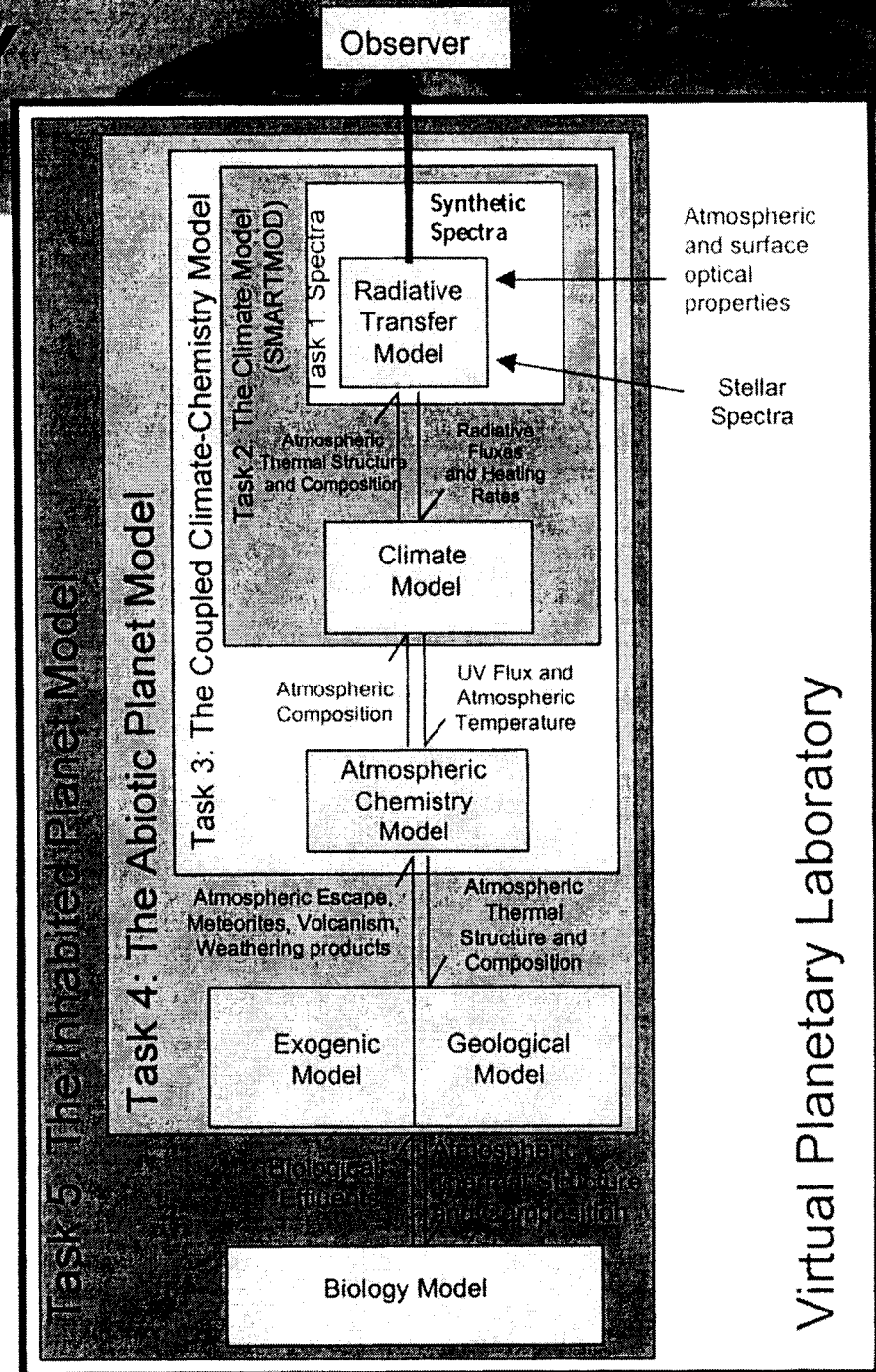


Oxygen domination of Earth's biogeochemistry did not occur until ~0.7-0.8 Gy ago. (Rain Forest, Hilo, Hawaii.)

Stromatolites may be a remnant of the **Archean** world. Built by the growth of layer upon layer of photosynthetic cyanobacteria, these colonies may have been the only life on Earth for 2Gy. With the advent of metazoan "grazers" they became uncommon, but extant stromatolites are found in a few places such as Shark Bay, Australia where the high salinity of the water inhibits predatory life. (Photo M. Martin, Deakin Univ.)

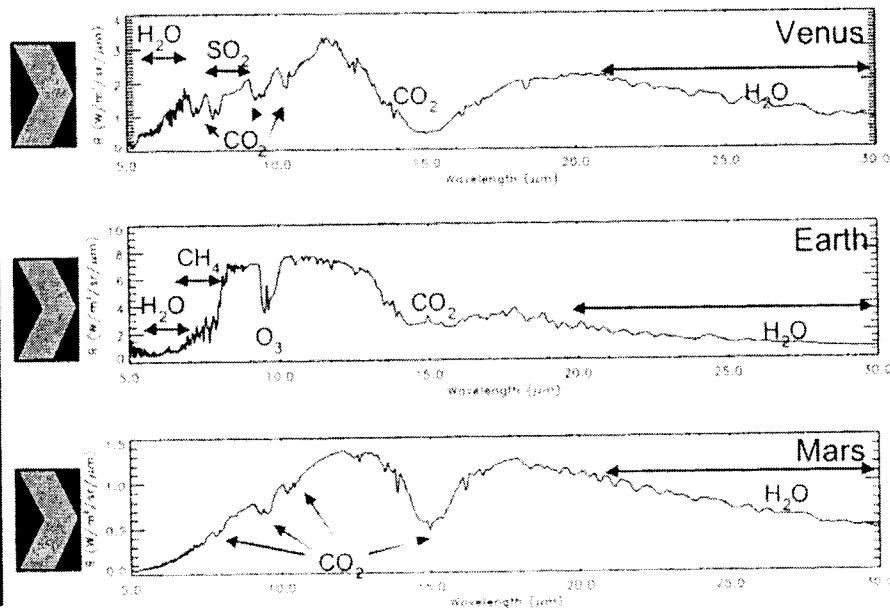
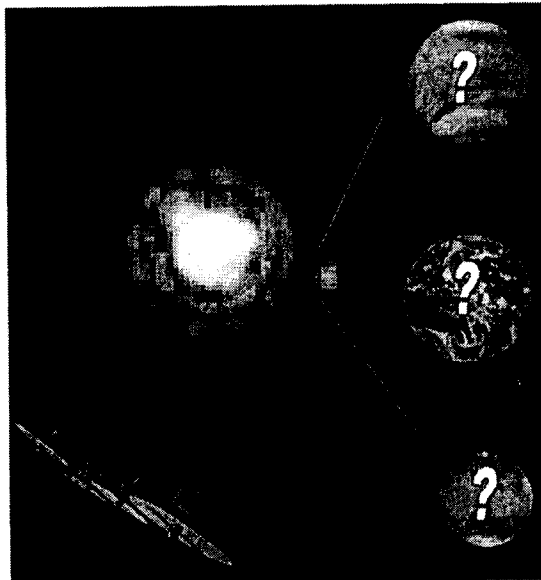
THE VIRTUAL PLANETARY LABORATORY

- Constructed with five successive tasks.
- Each task produces a range of synthetic spectra to identify habitable planets or potential biosignatures, and to derive astronomical instrumentation requirements.
- The VPL will:
 - improve modeling methods, inputs and computational efficiency.
 - cover a broad range of wavelengths
 - consider planets other than Earth, around stars other than our Sun.
 - include non-oxygen producing life
 - ultimately provide a comprehensive, **flexible** tool which can be used by a broader community.



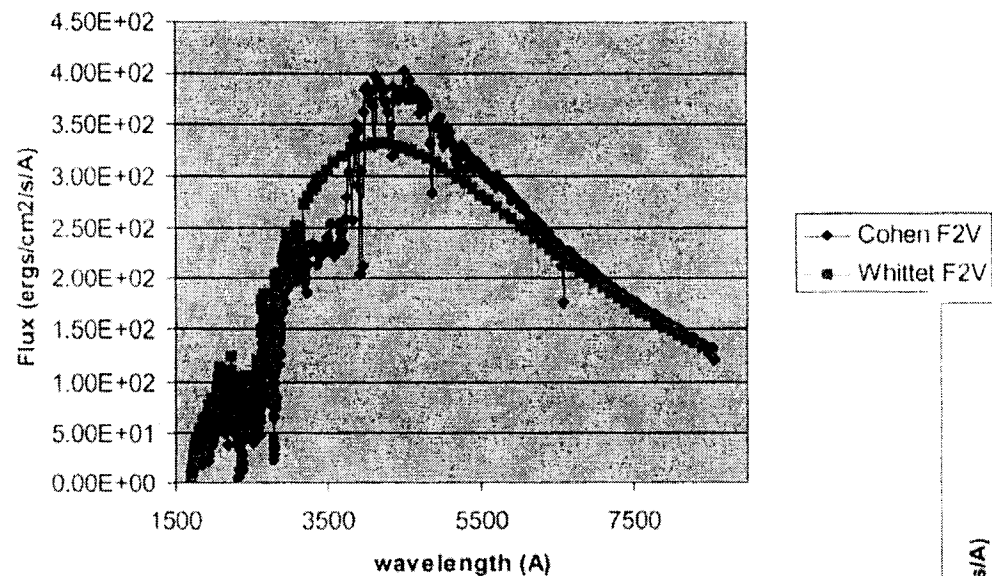
VPL RESEARCH GOALS

- 🌐 To understand the plausible range of atmospheric and surface compositions for terrestrial planets, and
- 🌐 To learn how to use spectra to discriminate between extrasolar planets with and without life.
- 🌐 The results will drive the design and search strategies for future planet detection and characterization missions.



Realistic Stellar Spectra

Whittet v. Cohen Spectra - F2V

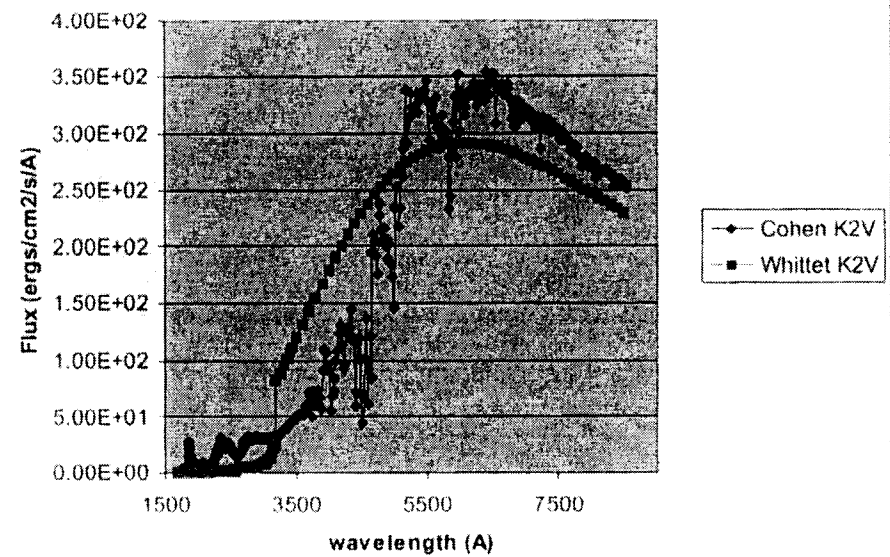


“A star is *not* a blackbody”.

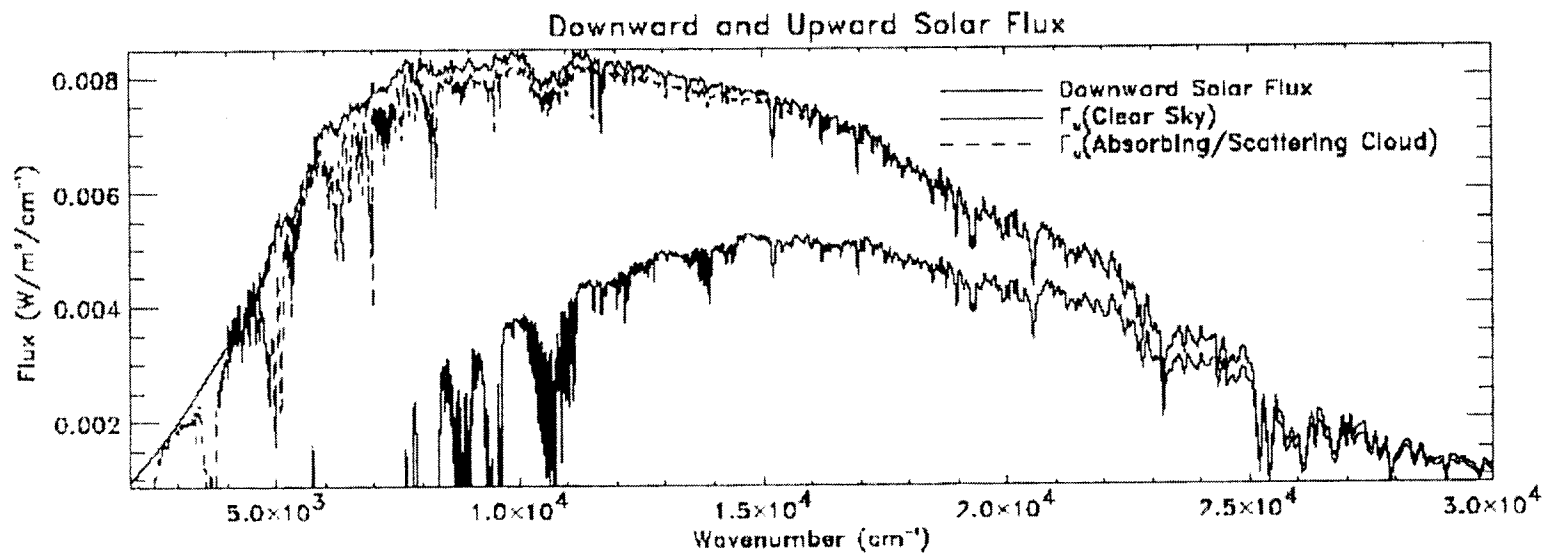
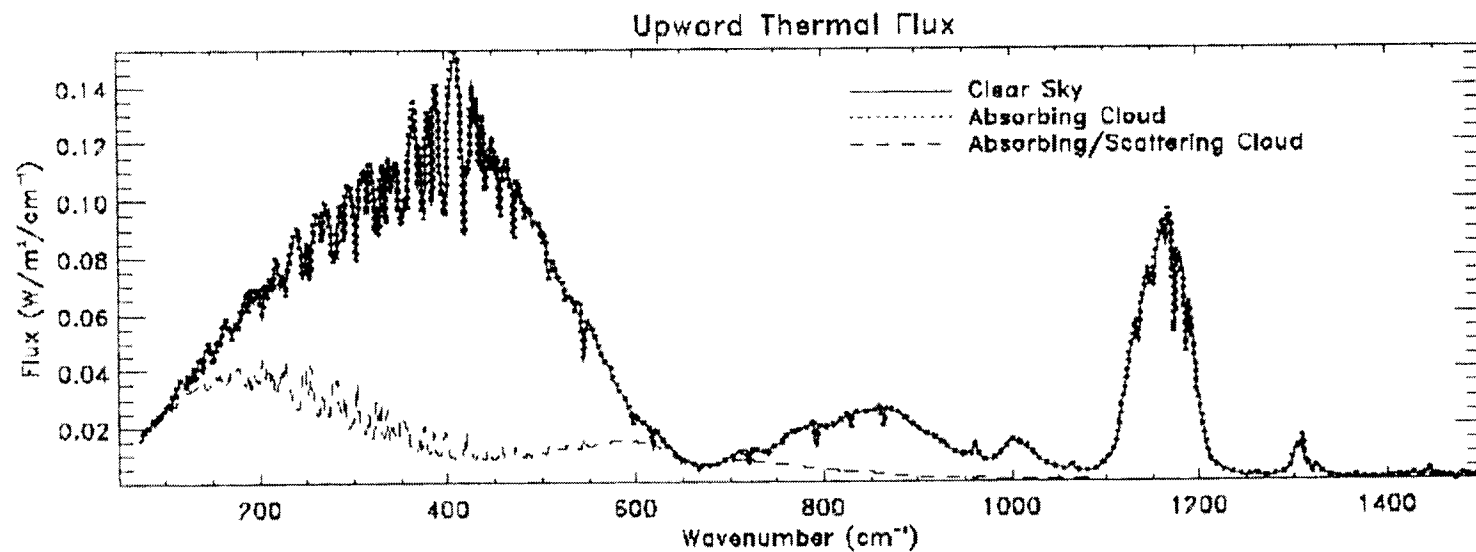
- Martin Cohen

- Accurate UV spectra are important for photochemical models
- Accuracy at longer wavelengths impacts climate models and atmospheric structure

Whittet vs. Cohen Spectra - K2V

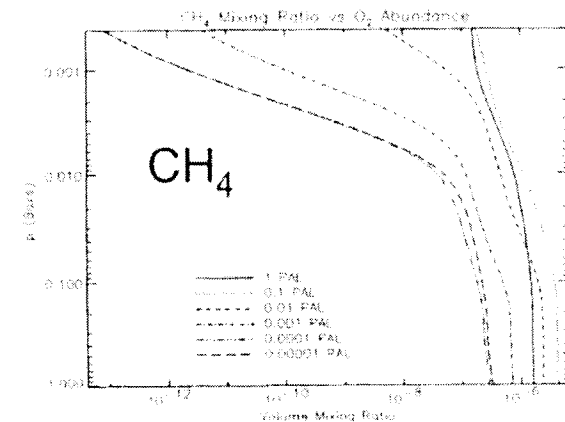
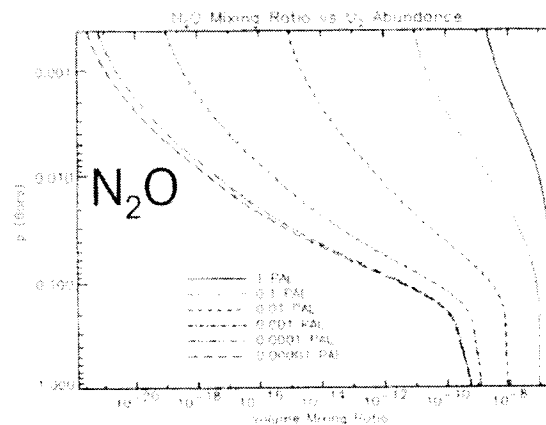
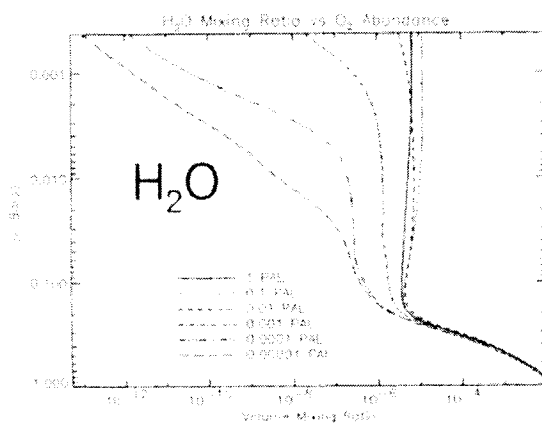
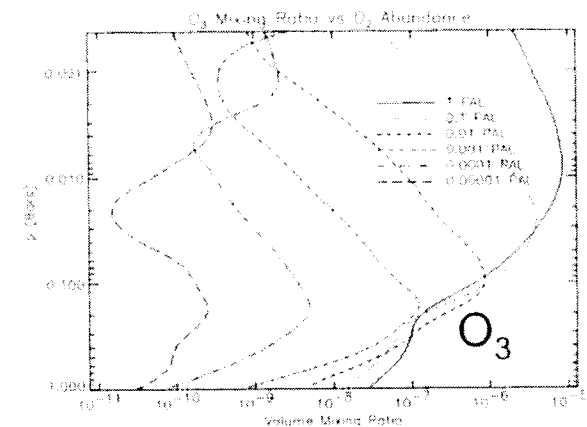
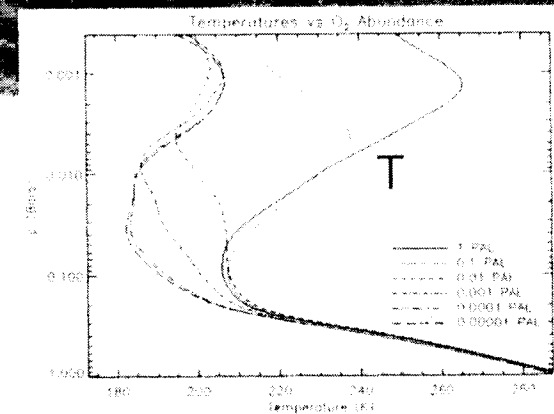


Realistic Clouds



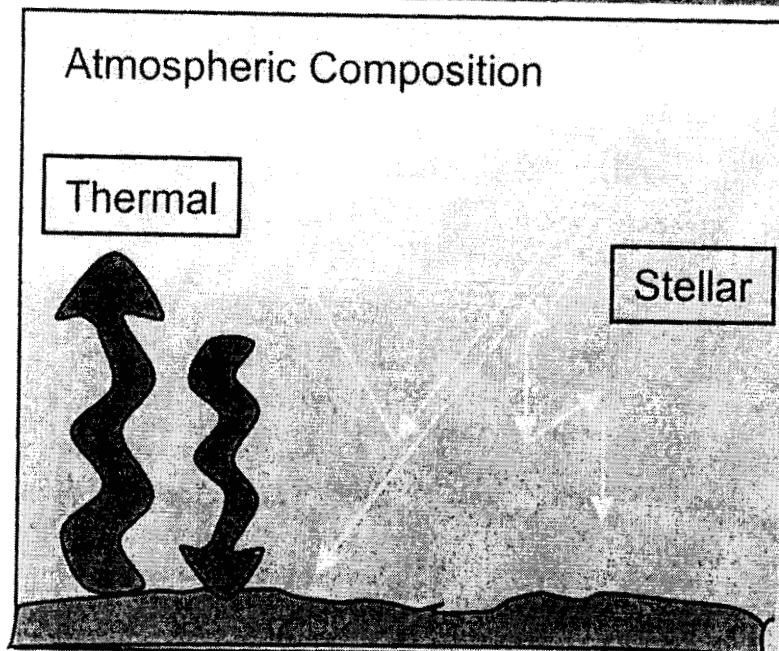
Model Atmospheres

- 1-Bar “Earth-like” model atmospheres developed with molecular oxygen (O_2) mixing ratios varying from present-day values (20.99%) to 1×10^{-5} of its present-day values. (Kasting and Krelow)
- The atmospheric temperatures and composition were allowed to evolve to a near-equilibrium state at 1 AU from a solar-like (G2) star.
 - Abundance of ozone (O_3), water vapor, (H_2O), methane (CH_4), and nitrous oxide (N_2O) decrease with O_2 abundance
 - Particularly in the stratosphere
 - Stratospheric temperatures cooled substantially with loss of ozone



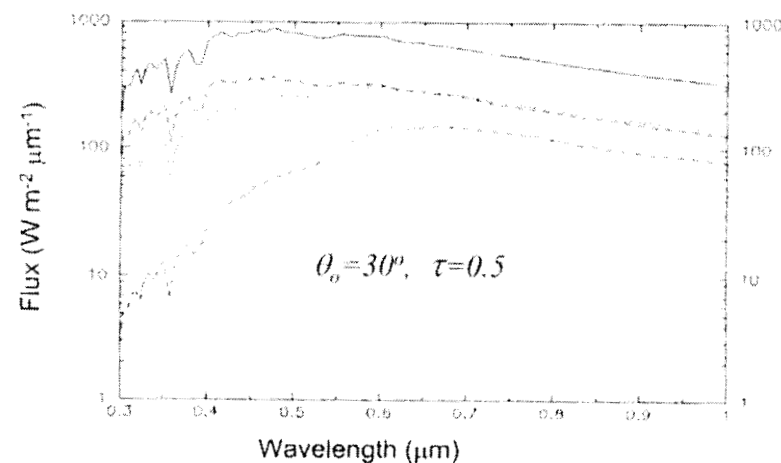
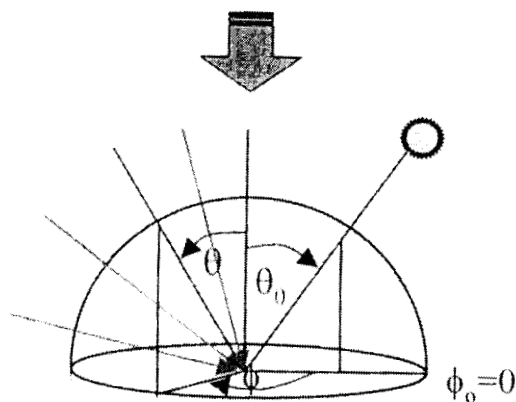
Radiative Transfer Model

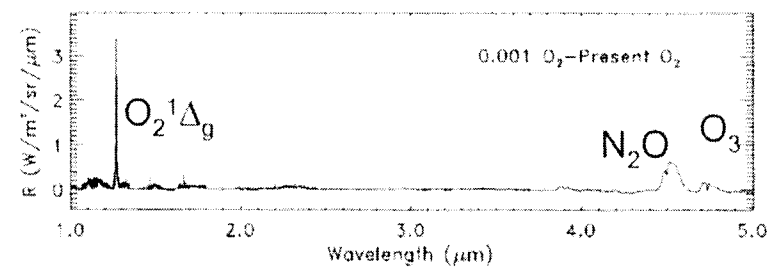
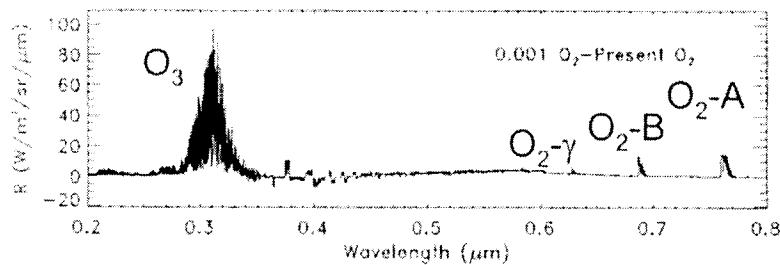
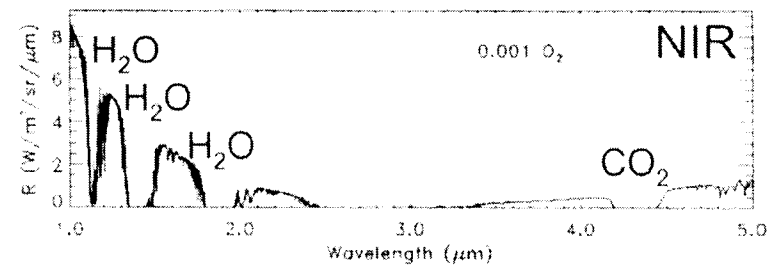
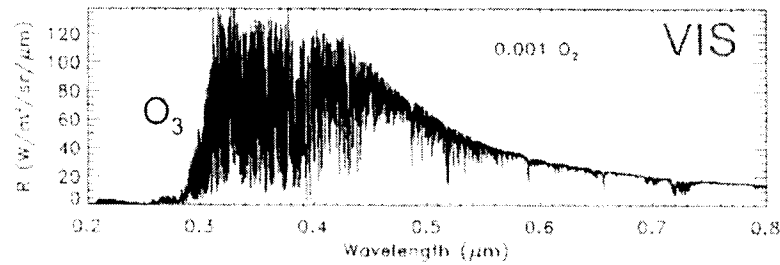
Atmospheric Composition



Simulating the radiation field (Crisp)

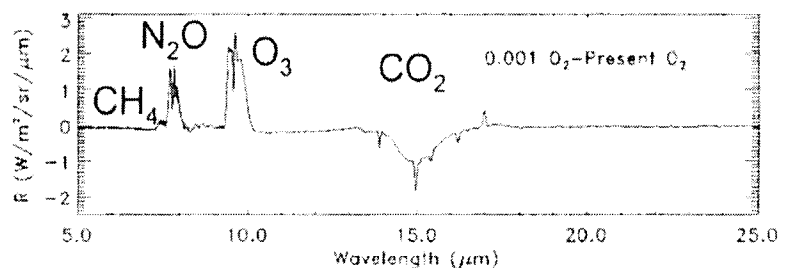
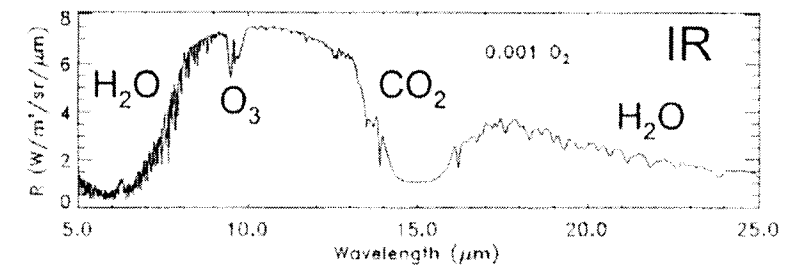
- Resolve the spectral dependence of gases, cloud, aerosols, surface albedos and radiation sources.
- Multiple Scattering Model
- Gas Absorption
 - Line-By-Line model for IR vibration-rotation bands
 - Includes absorption by H_2O , CO_2 , O_3 , N_2O , CH_4 , and O_2
 - UV Absorption: DeMore et al. (1992)
- Single Scattering Optical Properties of Clouds and Aerosols
- Lambert surfaces with wavelength dependent albedos



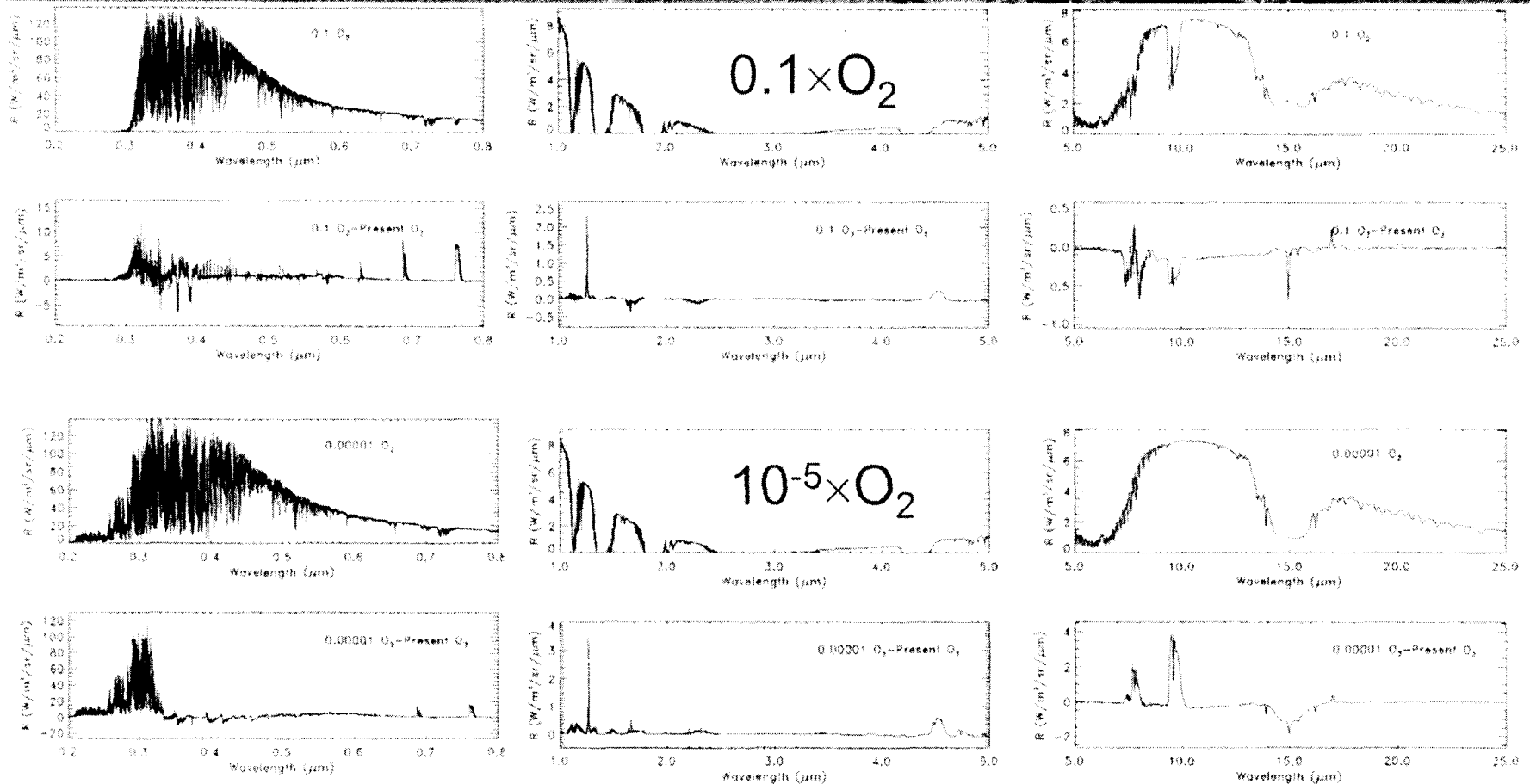


SPECTRAL RADIANCE DIFFERENCES

Variations in trace gas abundances associated with different O_2 abundances produce a range of distinctive spectral features at in the reflected stellar radiances and in the emitted thermal radiances.



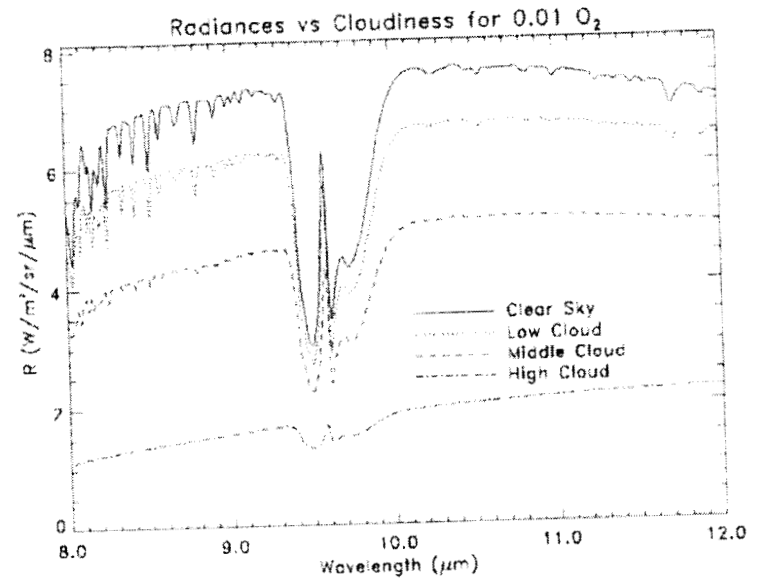
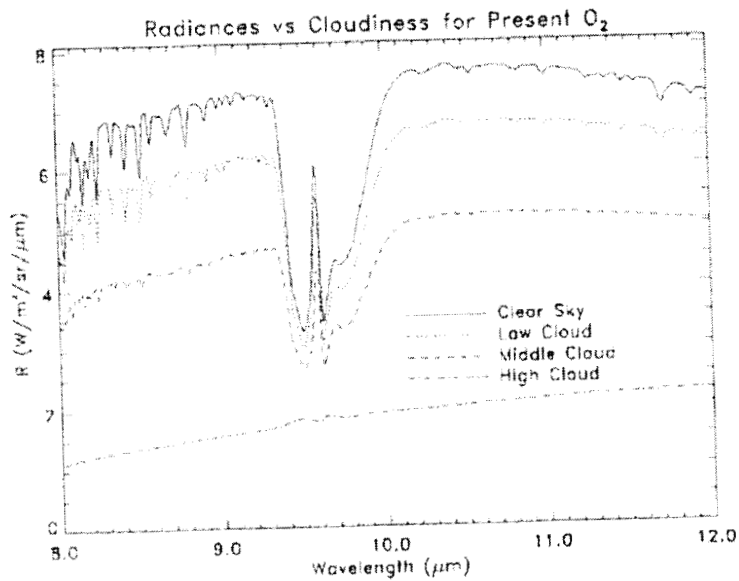
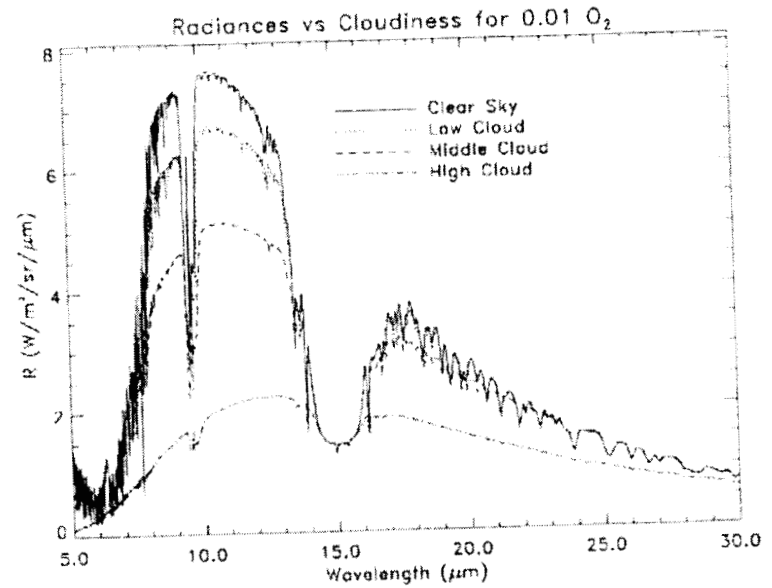
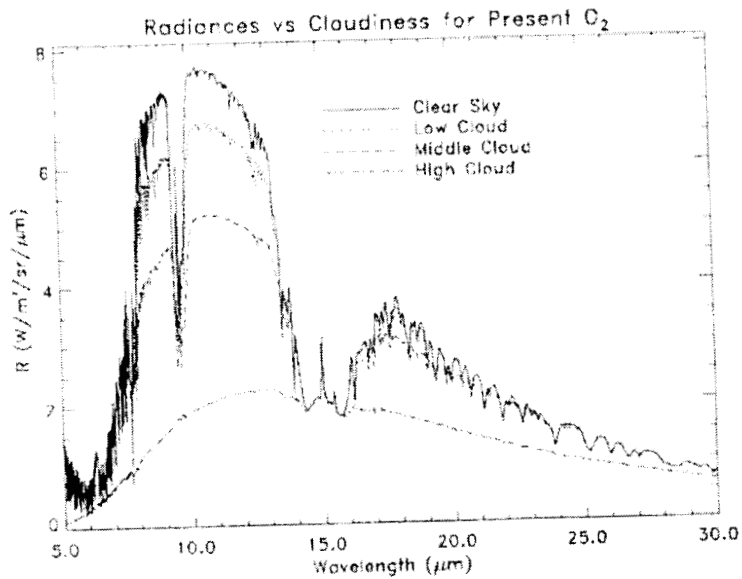
Spectral Differences vs. O_2 Abundance



- High-resolution spectral radiances computed for each model atmosphere
 - Stellar illumination spectrum
 - Thermal emission spectrum

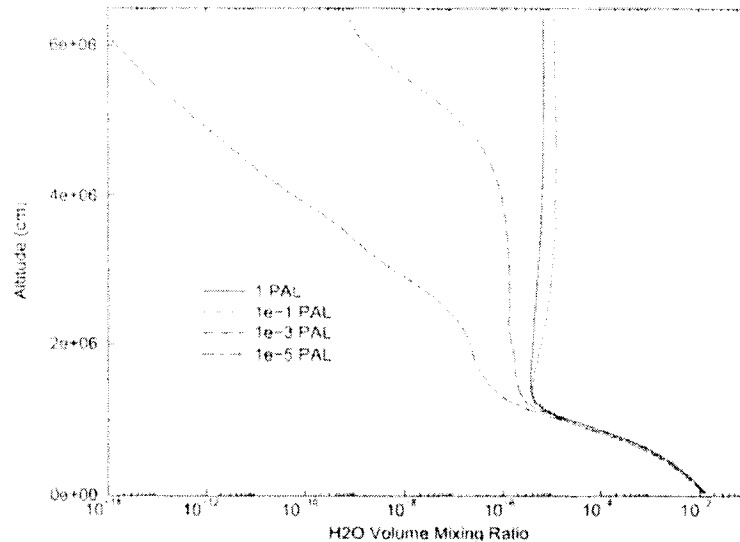
- All spectra shown for
 - Global Average atmospheres
 - **Cloud-free conditions**
 - Dark ocean surface

The Effect of Clouds

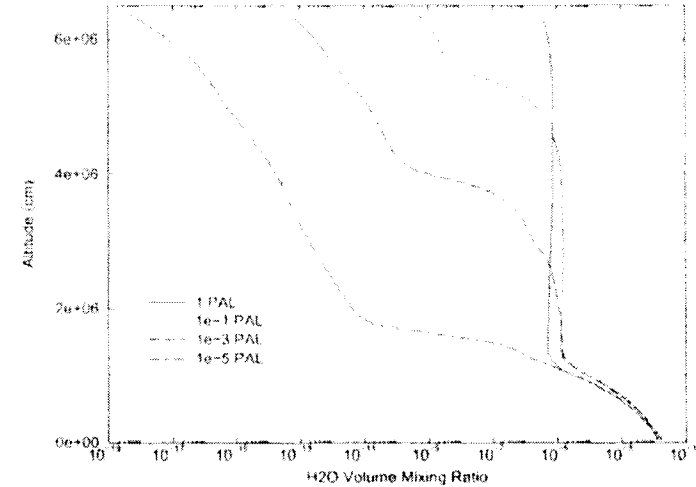


Current Work

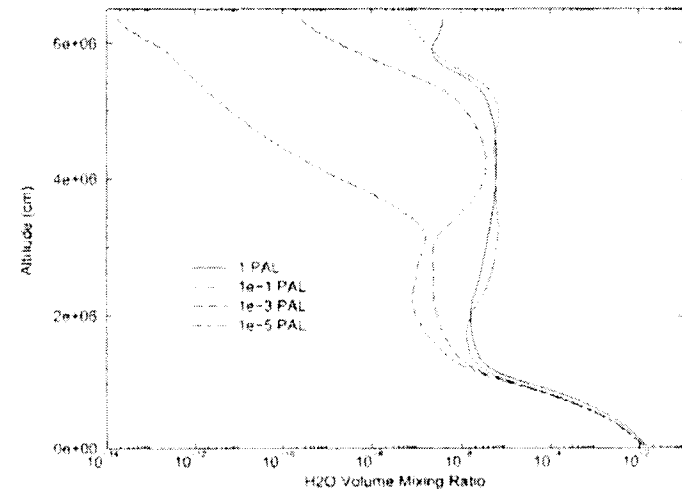
H₂O Profiles for Solar Spectra
at selected O₂ levels



H₂O Profiles for F2V Spectra
at selected O₂ levels



H₂O Profiles for K2V Spectra
at selected O₂ levels



- Modeling self-consistent atmospheres for planets around other stars
- Producing spectra of these cases

✓

